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Trapped individual ion at absolute zero temperature

(ultra-high-vacuum trap/zero-point confinement/laser cooling/minimum micromotion)

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ABSTRACT **Laser cooling and ion trapping have progressed to such an extent that one can now speak of realizing a confined atom at absolute zero temperature. In this short publication, we analyze an experiment toward such realization using a single Ba^+ ion in a miniature rf trap. The Ba^+ ion is first laser-cooled to the limit where the ion spends most of its time in the zero-point energy state. Then a test sequence allows one to verify whether or not the ion is actually in its zero-point state. The test sequence may also serve as a device for state selection of an atom at absolute zero temperature.**

Trapping of ions in small quadrupole traps has been developed in the last two decades or so. Recent progress in laser cooling makes it possible now to cool the ions to a very low temperature (1, 2). For a single ion confined in a harmonic potential as in a Paul trap, if the ion stays in the zero-point energy (ground) state without any excitations, it is said to be in total zero-point confinement—the quantum analogue of a particle at rest in space. Then the state of the ion cannot be distinguished from that of an ion in contact with a reservoir at 0 K.

It can be shown that, with the single-laser sideband cooling technique of an atom in a three-dimensional trap (1, 3, 4), the minimum average vibrational quantum number in each degree of freedom for $\omega_{vx} \approx \omega_{vy} \approx \omega_{vz} \approx \omega_v$ is

$$\langle v_i \rangle_{min} \approx \{g(\omega) + g(\omega - \omega_v)\}/\{g(\omega + \omega_v) - g(\omega - \omega_v)\},$$
$$1/g(\omega) = 1 + \{2(\omega - \omega_0)/\gamma\}^2,$$

where $i = x$, y, or z, ω_v is the secular oscillation frequency, and γ is the linewidth of the cooling transition. By using a standing wave laser beam with the atom at a node, one can suppress the carrier at ω [the term $g(\omega)$ in the expression for $\langle v_i \rangle_{min}$] and greatly reduce $\langle v_i \rangle_{min}$. This means that, in a realistic three-dimensional case, if only $\omega_v \approx \gamma$, the atom can spend most of its time in the state $(v_x, v_y, v_z) = (0, 0, 0)$, or zero-point energy state. In our current work with Ba^+ ion, the cooling transition $6^2P_{1/2}$–$6^2S_{1/2}$ has a linewidth $\gamma \approx 21$ MHz. A miniature Paul–Straubel trap has been designed for this experiment (5). The small size and high rf voltage allow a much stronger trapping field and therefore ω_v could easily be comparable to or larger than 21 MHz. To ensure the ion is cooled down to the zero-point in all three dimensions with only one laser beam, the ring of the trap is made slightly elliptical to make the oscillation frequencies along the three axes nondegenerate and the cooling laser beam is directed along the body diagonal (1).

Assuming $\omega_v \approx \gamma$, then with a standing wave cooling laser, $\langle v_i \rangle \approx 0.06$. This means that, after completion of the cooling process, about 83% of the time the trapped ion will be found in the $S(0, 0, 0)$ state! Even for $2\omega_v \approx \gamma$ and a running wave laser, one gets a small but usable percentage. By using the quantum jump and shelving technique (6), one can experimentally show exactly when and for how long the ion remains in the $S(0, 0, 0)$ state. First, the cooling laser is turned off after the cooling limit has been reached. Then, a second laser is turned on for a period of time to make the resonant $6^2S_{1/2}$–$5^2D_{3/2}$, $\Delta v_i = 0$ transition. Hereafter, pulsing the interrogating laser (the same as the cooling laser) will not induce the strong fluorescence provided the ion has made the transition to the metastable D state. The second laser is then tuned to the upper vibrational sideband frequency and pulsed to quench the metastable D state by means of the transition $5^2D_{3/2}$–$6^2S_{1/2}$, which has a lifetime of 30 s. In this transition a jump $\Delta v_i = -1$ must occur. If the ion is in the $D(0, 0, 0)$ state [i.e., the ion was in the $S(0, 0, 0)$ state at the end of the cooling process], the D state cannot be quenched and pulsing the interrogating laser will not induce fluorescence. However, if the ion is in a D state other than the $D(0, 0, 0)$ [i.e., the ion was in higher vibrational state than the $S(0, 0, 0)$ state at the end of the cooling process], the transition to the S state will occur and so does the fluorescence. Thus, absence of fluorescence after the quenching laser was pulsed on is a clear signature that the ion is in the zero-point state $S(0, 0, 0)$ right before the test sequence. In fact, the test sequence can start at various time intervals τ after cooling. If no fluorescence occurs in a few consecutive test sequences, it is almost certain that the ion has been in zero-point confinement for the time τ.

It should be further pointed out that, although the above test sequences can verify whether or not an atom is in its zero-point energy state, it should also serve as a state preparation process. In fact, once the atom is in the $D(0, 0, 0)$ state, it can be quenched or allowed to spontaneously decay into the $S(0, 0, 0)$. Therefore, one now has an atom totally confined to the quantum limit at one's disposal. In other words, our scheme combines previously demonstrated laser sideband cooling with a kind of Maxwellian demon that picks out the desired zero-point state $(v_x, v_y, v_z) = (0, 0, 0)$.

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